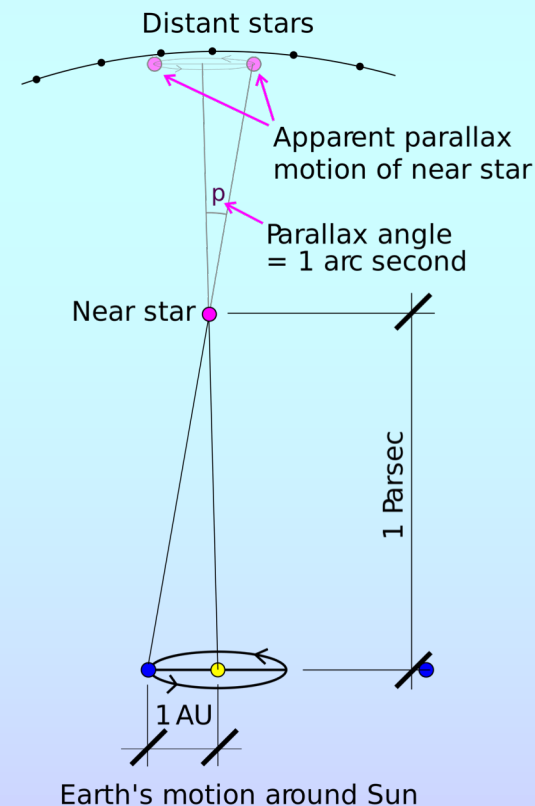


Numbers to Keep in Mind

- $R_{\odot} \sim 7 \times 10^{10} \text{ cm}$
- $M_{\odot} \sim 2 \times 10^{33} \text{ gm}$
- $L_{\odot} \sim 4 \times 10^{33} \text{ ergs/sec}$
- $1 \text{ pc}^* = 3.1 \times 10^{18} \text{ cm} = 206265 \text{ A.U.}$
- $M_{\odot}(\text{bol}) = +4.74$
- $1 \text{ arcsec/year at } 1 \text{ pc} = 4.74 \text{ km/sec}$

*1 parsec = distance where parallax is 1 arcsec
 $d(\text{parsec}) = 1/p$ where p is parallax in arcsec



Determining Stellar Luminosities

The only **direct** way of measuring the luminosities of stars is through the application of geometry, and the inverse square law of light. There are several methods to do this:

- Parallax
- Moving Clusters
- ~~• Statistical and Secular Parallax~~
- Expansion Parallax and Light Echoes

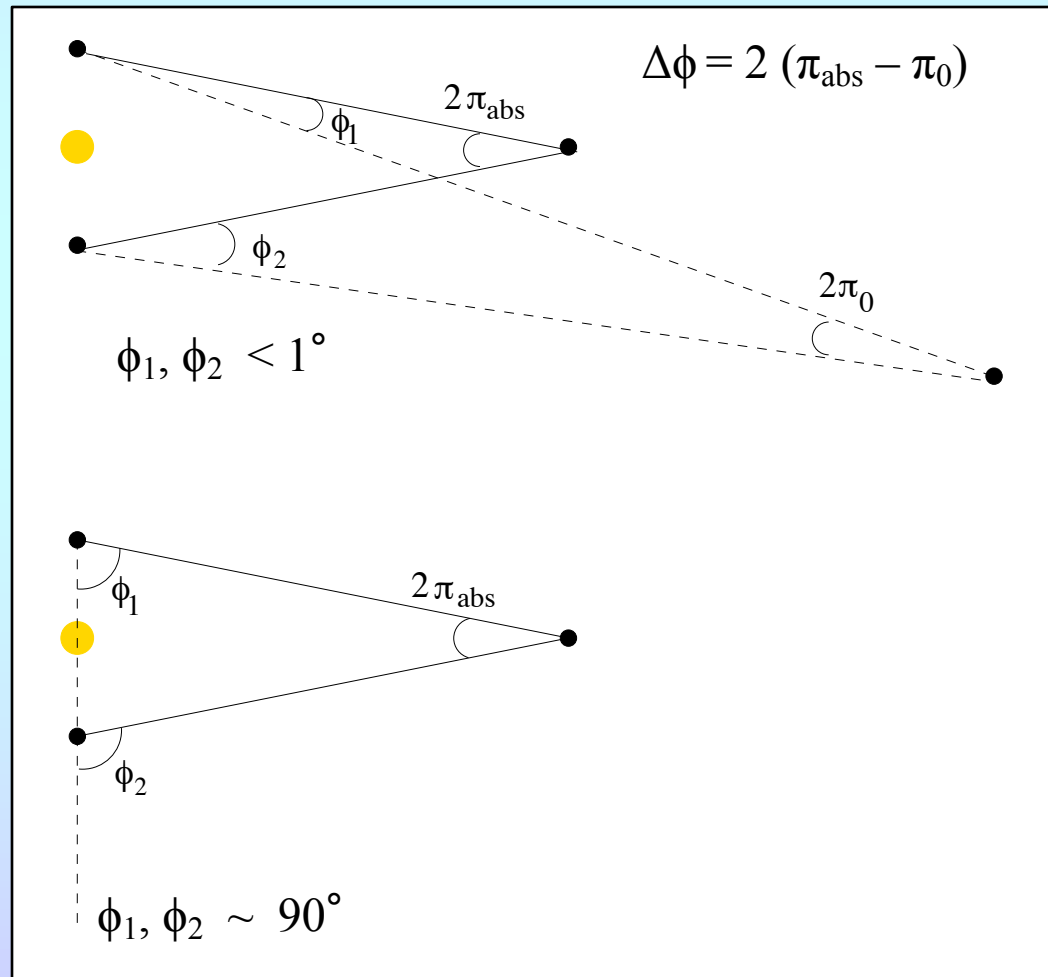
Every other method of determining distances is secondary (i.e., it relies on knowing the luminosities or sizes of objects measured by one of these techniques).

Parallax Measurements

Ground-based observations can only produce relative parallax measurements. To obtain absolute parallaxes, one needs a model for the Galaxy (or a special space mission).

Ground-based parallaxes depend on the distances to the background field stars; space missions such as Hipparcos and Gaia obtain absolute parallaxes by using reference stars $\sim 90^\circ$ away.

Note: the very closest star has a parallax of $\sim 0.75''$; these angles are *tiny*.



Astrometric Catalogs

- 1855: Bonner Durchmusterung (BD)
 - Pre-photographic, $\delta > -23^\circ$; 325,000 stars; $m < 10$
- 1892: Córdoba Durchmusterung (CD)
 - Southern extension to BD, $\delta < -22^\circ$; $m < 10$
- 1896: Cape Photographic (CP)
 - Photographic catalog, $-30^\circ < \delta < -40^\circ$ and $\delta < -52^\circ$; 68000 stars
- 1918: Henry Draper (HD) and Henry Draper Extension (HDE)
 - All sky magnitudes *and* spectral types; $m < 9$; 360,000 stars
- 1950: Yale Bright Star (BS or HR)
 - Colors, magnitudes, and parallax for 9,100 stars; $m < 6.5$
- 1963: FK4, FK5, and FK6 (Fundamental Catalogs)
 - Reference frame precision parallaxes for 1535 stars

Astrometric Catalogs

- 1990: Hipparcos satellite catalog
 - Absolute precision parallaxes for 100,000 stars with $m < 8$; lower precision data for 2,500,000 other stars to $m < 11$ (Tycho)
- 1994: Digitized Sky Survey (I and II)
 - Digitized version of Palomar and UK Schmidt plates; rough magnitudes and astrometry for $\sim 10^9$ objects to $m < 21$
- 2003: USNO-B
 - Digitized version of Palomar and UK Schmidt plates; astrometry and rough magnitudes for $\sim 10^9$ objects to $m < 21$
- 2003: 2 Micron All Sky Survey (2MASS)
 - Infrared (JHK) positions and magnitudes to $m < 15$
- 2005: Naval Observatory Merged Astrometric Dataset (NOMAD)
 - Compilation of data taken from Hipparcos, Tycho, USNO-B, 2MASS, UCAC-2, and other catalogs; $\sim 10^9$ stars to $m < 21$

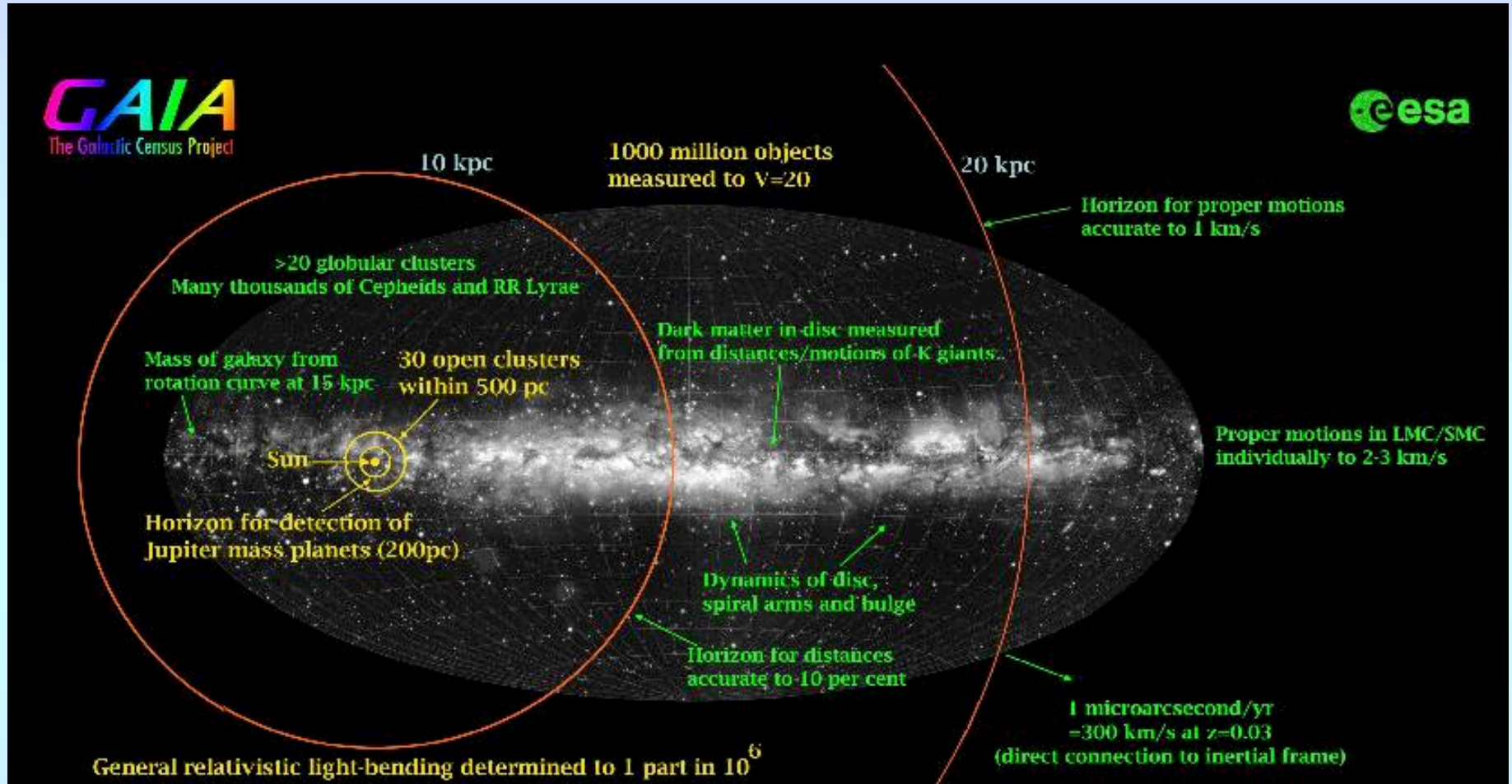
Astrometric Catalogs

- 2009: 3rd USNO CCD Astrograph Catalog (UCAC-3)
 - Uniform astrometry for 10^8 stars with $8 < m < 16$
- 2010: Proper Motion Catalog Combining USNO-B and 2MASS (PPXML)
 - Proper motions for $\sim 10^9$ stars with $m < 20$
- 2017: Gaia satellite catalog
 - Follow-on to Hipparcos; 10^9 stars with ultra-precise parallax and proper motions to $m < 21$; used Hipparcos as first epoch
- 2018: Gaia DR2
 - Proper motions separated from parallaxes based solely on Gaia data

Continual Problem with Parallax: Rare Objects

Type of Object	Density	V mag
Open Clusters	5 within 200 pc	3 - 20
Globular Clusters	0 within 2 kpc	---
Cepheid Variables	8 within 500 pc	3 - 6
RR Lyrae Variables	1 within 500 pc	8 - 9
Other Horizontal Branch	~10 within 500 pc	7 - 9
Bright Red Supergiants	0 within 500 pc	---
Bright Blue Supergiants	1 within 500 pc	1
High Latitude Supergiants	2 within 1 kpc	6 - 7
Carbon Stars	13 within 500 pc	5 - 21
Planetary Nebulae	~10 within 500 pc	11 - 16
Cataclysmic Variable	~30 within 350 pc	12 - 16

GAIA Survey



V	10	11	12	13	14	15	16	17	18	19	20	21
σ (μ arcsec)	4.0	4.0	4.2	6.0	9.1	14.3	23.1	38.8	69.7	138	312	1786

For comparison, Hipparcos measured 10% parallaxes to $V \sim 8$

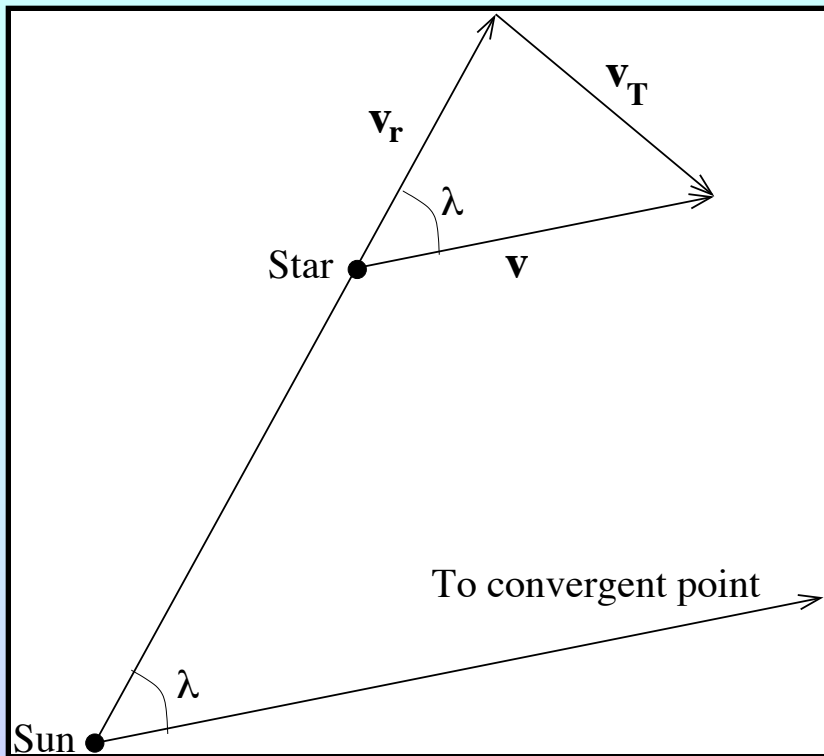
Moving Cluster Method

Premise: For a nearby cluster, both the tangential (proper) motion (μ) and radial velocities (v_r) of stars are measureable.

$$v_T = \mu D$$

$$v_r = v_r$$

The ratio of these two quantities can be determined by looking for the convergent point of a cluster.



$$\tan \lambda = \frac{\mu D}{v_r} \Rightarrow D = \frac{v_r \tan \lambda}{\mu}$$

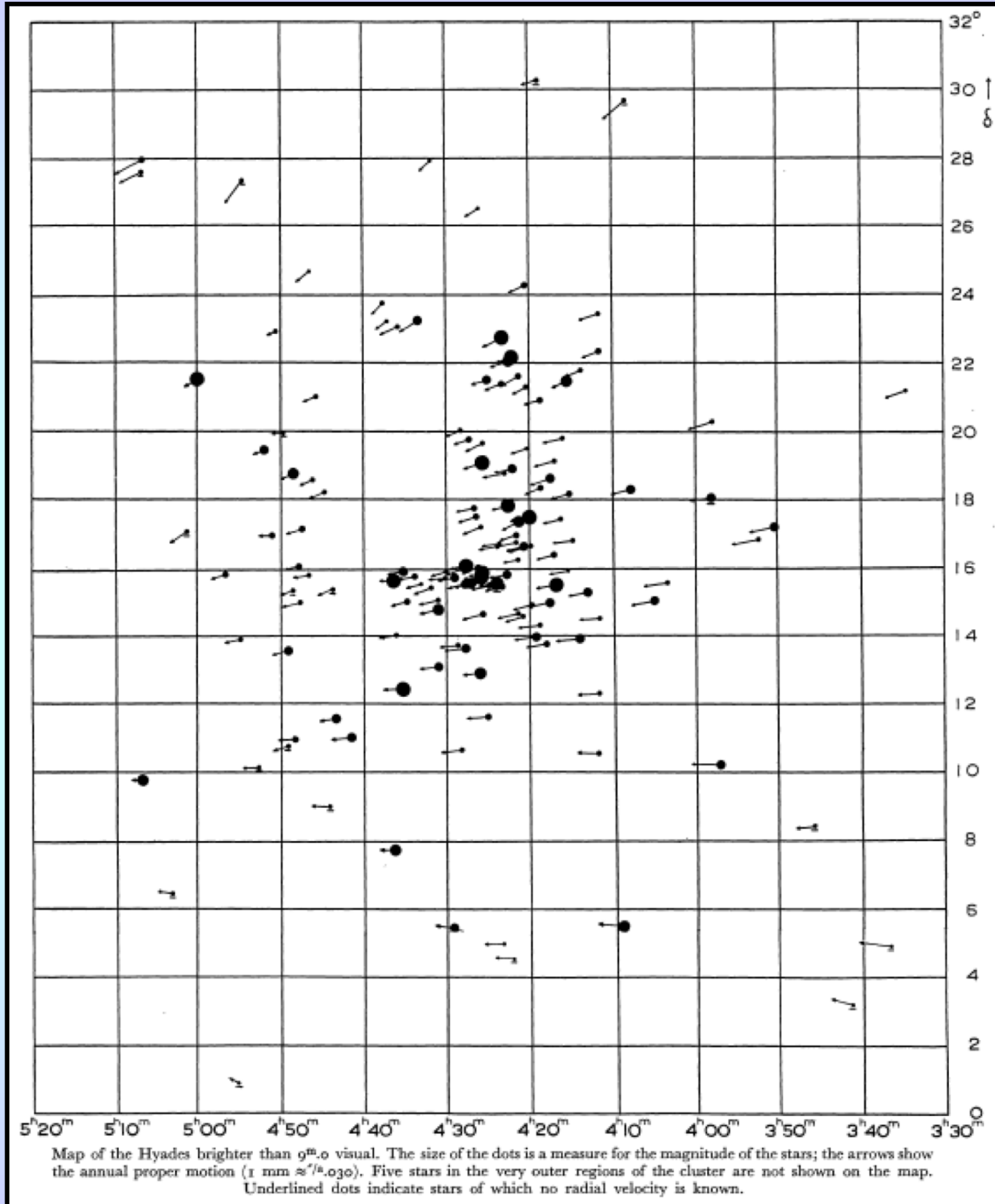
If v_r is in km/s and μ is in arcsec/yr, then

$$D(\text{pc}) = \frac{v_r \tan \lambda}{4.74 \mu}$$

The Hyades

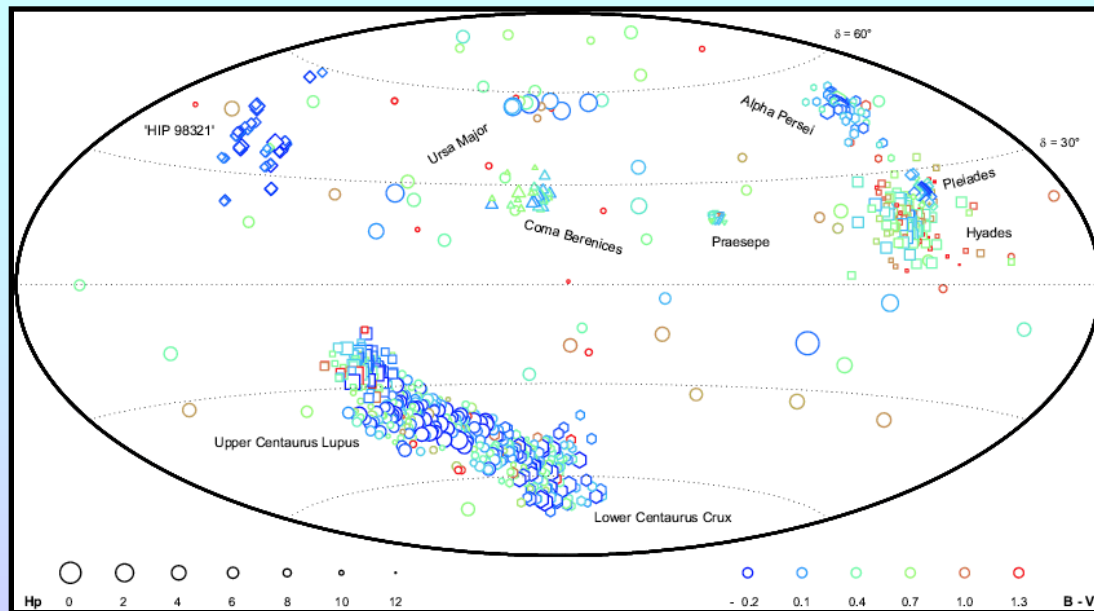
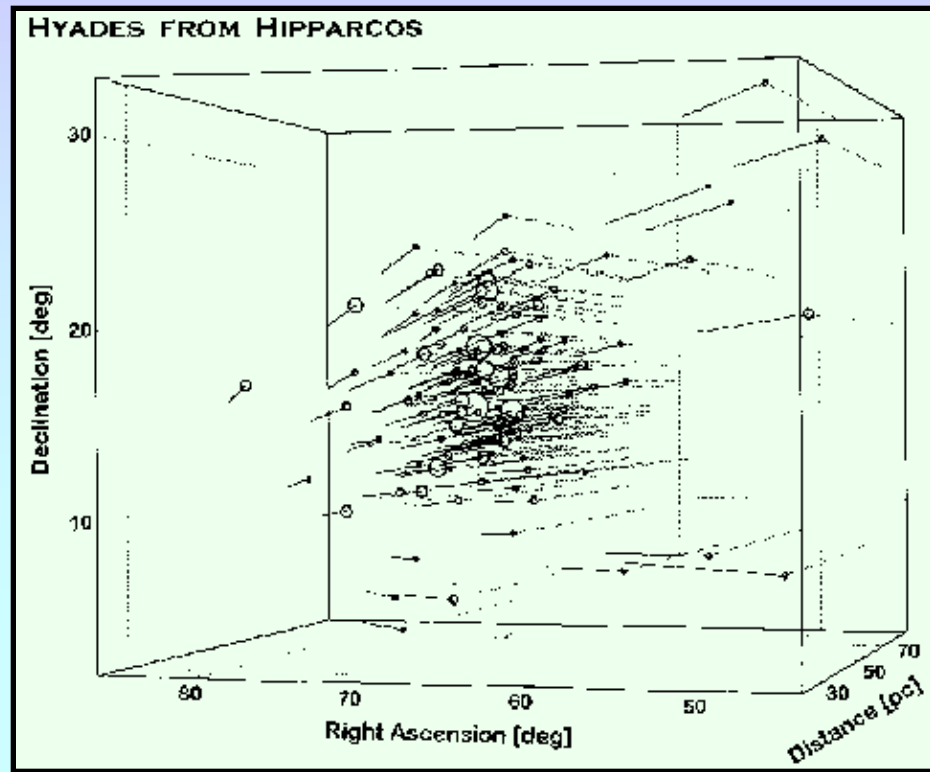
The most famous example of a moving cluster is the Hyades.

[van Bueren 1952, Bull. Astro. Inst. Neth, XI 432, 390]



Moving Cluster Method

Moving cluster distances are available for a few nearby star clusters, such as (famously) the Hyades ($D \sim 45 \pm 1$ pc). The diagram below shows all the clusters done by the Hipparcos satellite.



Statistical Parallax

[Mihalas & Binney 1981, “Galactic Astronomy”, p. 409]

Premise: The Sun’s motion through space (as reflected in the proper motions of stars) can be used as a baseline for parallax. The trick is to choose a homogeneous sample of stars (all with the same brightness and distance) distributed across the sky.

Terminology: there are two types of “statistical parallax”

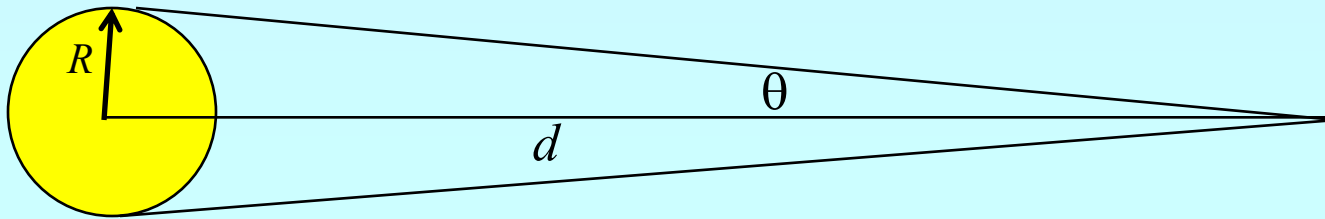
- Secular Parallax: Uses proper motion data in the direction of the solar motion
- Statistical Parallax: Combines proper motion data perpendicular to the solar motion with radial velocity data

Warning: For these methods to work, there must be no kinematic or photometric biases. (In other words, Galactic rotation is a problem.)

Thanks to GAIA, we no longer need this technique.

Expansion Parallax

For a few objects (such as novae), it is possible to estimate their distance (and therefore their luminosities) via their angular size.



If you measure their expansion velocity, then $R = v t = d \theta$. Of course, you have to wait until your telescope resolves the object. (And there's the assumption of spherical symmetry to worry about.)

Baade-Wesselink Measurements

The distances (and luminosities) of pulsating stars can be obtained using a method developed by Walter Baade and Adriaan Jan Wesselink. In theory, it's very simple: at any time, the flux one sees from a star depends on its radius and temperature:

$$F = \frac{L}{4\pi d^2} = \frac{4\pi R^2 \sigma T^4}{4\pi d^2} \propto \frac{R^2 T^4}{d^2}$$

If the star is pulsating, then at any two times

$$F_1 \propto \frac{R_1^2 T_1^4}{d^2} \quad F_2 \propto \frac{R_2^2 T_2^4}{d^2}$$

The flux is measurable, and the temperature can be estimated from the star's color or spectrum. Thus, you have 2 equations and 3 unknowns (R_1 , R_2 , and d). But if you measure the expansion velocity of the star during its pulsation, then you have a third equation, $R_2 = R_1 + v t$. You can then solve for distance and luminosity.



Can anyone think of a way to directly measure the distance to this object? Suppose it is too far for parallax.

Other Luminosity Measurements

Note: There are many other methods for estimating the luminosities of stars, but each relies on the fundamental measurements discussed above. We'll talk about some of these towards the end of the course.

